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Envi-MET validation and sensitivity analysis using field measurements in a hot arid climate

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Abstract. Envi-MET is a computational fluid dynamics (CFD) modelling software that analyses interactions between the microclimate and the built environment through simulation, predicting parameters such as wind speed, air temperature and thermal comfort indices. The large number of variables and calculations involved makes validating Envi-MET models difficult. This study focuses on the validation of Envi-MET through sensitivity and calibration testing. A site was chosen in a hot arid climate location. The testing involved measuring air temperature, relative humidity and wind speed at the site. For the sensitivity testing a hypothetical site was modelled with three scenarios for four variables (wind speed, relative humidity, albedo and grid size) set as low, base and high values. The monitoring study concluded that the accuracy of Envi-MET varied with the variable in question, showing a high correlation factor with wind speed and air temperature but a poor correlation with relative humidity, especially between 04:00 and 10:00. Envi-MET displayed different sensitivity levels, with a good response to variables change in wind speed and relative humidity, but little response to albedo changes.

1. Introduction

Envi-MET has been described as “*a holistic three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions not only limited to, but very often used to simulate urban environments and to assess the effects of green architecture visions*” [1]. The software was developed by Michael Bruse and his team in 1993, and since then enhancements to the software have elevated it from a specialist research tool to mass market implementation [1]. Envi-MET as an urban simulation programme deals with large numbers of variables, and this makes the software potentially susceptible to calculation error. Considering that risk, this study investigated the accuracy of the outcomes of Envi-MET simulations by comparing them to field measurements made under hot arid conditions at Al Ahliyya Amman University in Jordan. The sensitivity of Envi-MET outputs to changes in the values of input variables was also analysed.

2. Previous validation studies of Envi-MET in hot climates

Early attempts to validate Envi-MET, for example [2][3], found adequate rather than strong levels of agreement between modelled and measured data. As Envi-MET developed and meteorological instrumentation improved, it became possible to undertake more detailed validation studies. Measurements of net-radiation, air temperature surface temperature and wind speed for an urban site in South Korea (hot humid climate) found significant differences between the logged and simulated results [4]. Conversely, monitored and modelled environmental conditions in the Al-Muizz street area of Cairo, Egypt (hot arid climate) found overall good agreement [5]. Wind speeds and other meteorological parameters were measured in Wuhan, China (hot summer climate) to assess the impact of tree type and distribution during a hot summer and cold winter. Envi-MET predictions showed good agreement for



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air temperatures whilst the findings for air velocities were less satisfactory – the measured wind speeds displayed more variability than the simulated values.

The results of this small literature review suggest that more validation studies of Envi-MET need to be performed under a range of climate types and urban/vegetative configurations. This need provided the motivation for the current work.

3. Methodology

3.1 Meteorological monitoring for Envi-MET comparison

The study site was Al Ahliyya Amman University in Jordan. This site offered a range of different urban elements, such as a wide variety of vegetation, tiled pathways, buildings and a car park (see Figure 1); the area surrounding the university is a hillside with empty plots and some scattered buildings. Trees at the edges acted as wind blockers. In addition, the University has 24 hour security that ensured the safety of the monitoring equipment. The Köppen climate classification system puts Jordan in two classifications - hot arid desert (BWh) and cold arid desert (BWk) [6], with a maximum temperature in August of 41.5°C and a minimum in February -4.5°C, Precipitation mostly occurs in winter, with an average of 55 rainy days. The cladding of most University buildings is white limestone with an average albedo of 60%, and the pathways that link the buildings have different material. However, the area where the loggers were placed was tiled with grey cement tiles with an average albedo of 30%. The locations of A and B allowed for different conditions, with B being near to sprinklers and A being under larger thicker trees. The vegetation at the site is mostly local and coniferous in nature - the only deciduous tree is *Populus nigra*. other coniferous are *Pinus halepensis*, Mediterranean cypress (*Cupressaceae*), *Phoenix dactylifera* and *Cupressus macrocarpa* 'Goldcrest' (Figure 2).



Figure 1. Rendering of the site showing the monitored locations.



Figure 2. Tree types found at the measurement site.
Courtesy of Al Ahlivva Amman University.

For comparison with Envi-MET predictions, the meteorological parameters measured at the two sites identified in Figure 1 were wind speed, air temperature, relative humidity and mean radiant temperature. Two Kestrel 5400 Heat Stress Trackers were used to log these parameters. The Kestrel 5400 is a handheld, portable WBGT (Wet Bulb Globe Temperature) logger and weather station. The quoted accuracies of the Kestrel readings are $\pm 3\%$ for wind speed; $\pm 0.5^\circ\text{C}$ for air temperature; $\pm 2\%$ for relative humidity.

3.2 Envi-MET sensitivity analysis

In order to test the sensitivity of Envi-MET, a hypothetical site was constructed and modelled in three scenarios of low, base and high settings. The tested meteorological parameters were wind speed, relative humidity, albedo of the surrounding surfaces and grid size. The evaluation of the data was based on the change in air temperature for the different scenarios

3.3 Statistical analysis of the monitored and modelled data

Historically, one of the most widely used methods of model validation is Pearson's correlation coefficient r . It is defined as “the measure of the strength of the linear relationship between two variables” [7]. Pearson's correlation coefficient consists of the covariance of the data sets given and their standard deviations, with the resulting value of the correlation coefficient r ranging between +1 and -1, where 0 means no correlation within the data sets. Root Mean Squared Error (RMSE) is a dimensional metric used to identify how large the difference is between observed and predicted values of a parameter and to indicate how divergent the predicted data are from the observed values. RMSE consists of the square root of the sum of the squared variables difference divided by the number of the variables. Mean Absolute Error (MAE) is a dimensional metric used to measure the error between two sets of data. The formula consists of the sum of the absolute difference of the predicted and observed values over the number of variables. RMSE and MAE are widely used by climate researchers to test and validate predicted values. It has been argued that RMSE and other new measures, such as the index of agreement, were superior to Pearson's correlation coefficient for evaluating models [8]. The index of agreement ranges between 0 and 1, with 1 being perfect correlation and 0 no relationship between the predicted and observed values. Later research suggested that RMSE is not appropriate and replacing it with MAE should give a more accurate description of the model validation [9]. In recent years it has been argued that the replacement of RMSE with MAE is not an accurate representation of the model validation process, especially when there is a Gaussian error distribution. The use of a combination of model verification methods to reach accurate results was recommended [10].

4. Envi-MET modelling of the Al Ahliyya Amman University site

4.1 Spaces

A 3D model of the site was built using *spaces* —one of Envi-MET's components, where initial AutoCAD format drawings were used as a base for the model. Modelling in *spaces* is a grid system modelling with a default resolution of 2 metres. The 3D resolution was changed to $dx=1$ $dy=1$ $dz=1$ since the site in question is small enough to fit in the 60x60-pixel grid. *Equidistant* was chosen as the method of vertical grid generation as the highest point of the buildings only reaches 18 meters, which is enough to avoid any boundary issues that might occur due to the proximity to the upper limit of the model.

4.2 Vegetation

Envi-MET allows its users to create their own vegetation database through *Albero*. To be able to use *Albero* in Envi-MET, the leaf area density (LAD) must be determined. However, in this study there was no need to construct new vegetation since Envi-MET's library had similar trees to those on the site, and only some modifications on the existing Envi-MET's data base was made.

4.3 Wind

The wind speed values for the given simulated day at the monitoring site were extracted from the EPW file for the nearest weather station to the site. Usually, weather readings are taken in an open field 10 metres above ground level, which makes the readings potentially unreliable for an urbanized setting. It has been suggested that the wind speed values from a weather stations can be adjusted to suit an urban setting by using a ratio S - the ratio between the wind speed at a height H above the urban area (V_H) and the wind speed at 10m height in open flat country (V_{10}), where $10\text{ m} \leq H \leq 150$ [11]. Table 1 shows the S factor values for urban and suburban areas.

Table 1. S factor $S = V_H / V_{10}$

Height	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150
S (suburban)	0.6	0.73	0.82	0.89	0.94	0.99	1.04	1.08	1.11	1.14	1.18	1.21	1.24	1.27	1.29
S (urban)	0.36	0.47	0.55	0.62	0.68	0.73	0.77	0.82	0.86	0.89	0.93	0.96	0.99	1.02	1.05

Al Ahliyya Amman University is situated outside of the city Amman on a hillside; therefore, it does not fall under urban or suburban areas regarding to wind speed. The average wind speed was calculated as 4 m/s from a north westerly direction (291°).

4.4 Meteorological settings

The day chosen for the simulation was 1st October 2017- chosen for the mild conditions of the month, with average meteorological parameters. The values for air temperature and relative humidity were obtained from an EPW file, as shown in Table 2.

Table 2. Air temperature and relative humidity values for the 1st October

Hour	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00
Air temp (°C)	17.4	16.2	15	14.3	13.8	13.8	15.3	17.4	19.5	21.4	22.9	24.1
Rel humidity (%)	47	49	50	52	50	50	50	41	34	28	24	22
Hour	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00	24:00
Air temp (°C)	24.9	25.2	25.1	24.3	23	21.5	20.3	19.1	17.9	16.8	15.6	14.4
Rel humidity (%)	21	23	22	24	28	30	37	41	46	50	55	60

5. Results and discussion

5.1. Comparison of the measured and Envi-MET data

Figure 3 shows the predicted and measured values of air temperature at monitoring point A. Envi-MET values are generally lower than the logged ones by an average difference of 2.8 °C between the time intervals of 09:00-19:00 and 00:00-04:00. However, the predicted values show a slight increase for the time intervals 20:00-23:00 and 05:00– 08:00, with an average difference of 0.3°C. Overall, the two sets of data show a good correlation, with an index of agreement value of 0.886 and Pearson correlation coefficient of 0.933, as shown in Table 3.

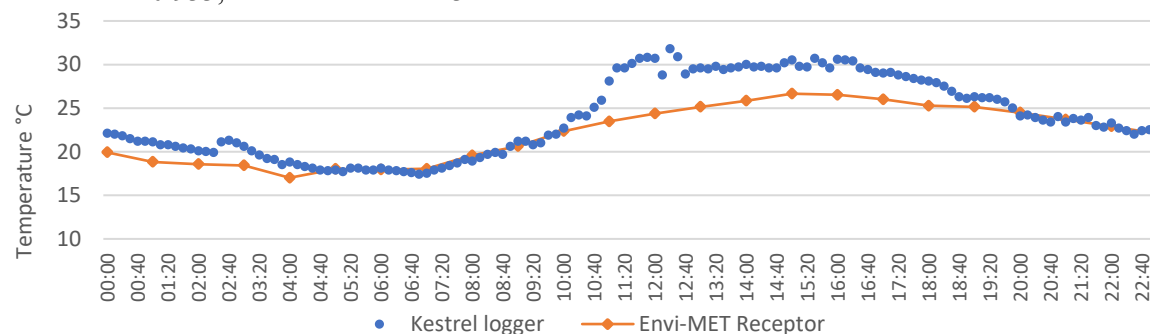


Figure 3. Data comparison between the observed and the predicted air temperature values, location A

Table 3. Model validation location A

Validation method	Temperature	Relative humidity	Wind Speed
Index of agreement	0.886	0.646	0.104
RMSE	2.602	18.797	0.424
MAE	1.974	14.4366	0.362
Pearson correlation coefficient	0.933	0.743	0.102

Figure 4 shows, for point B, the predicted temperature values for the time intervals of 09:00-19:00 and 00:00 – 04:00 are lower compared to the loggers' readings with an average change value of 2.9°C. For the rest of the day, the predicted values are similar to the observed ones, with a slight increase of an

average change value of 0.2°C. Overall, the two sets of data show a good correlation, with an index of agreement value of 0.890 and Pearson correlation coefficient of 0.934 (see Table 4).

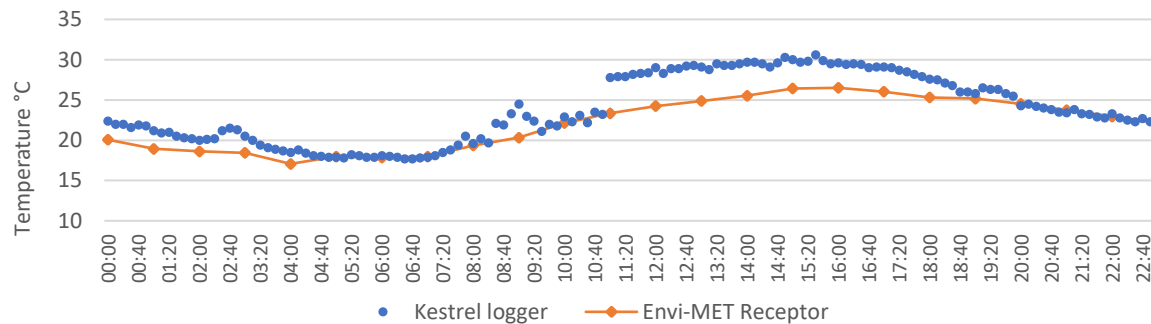


Figure 4. Data comparison between the observed and the predicted air temperature values, location B

Table 4. Model validation location B

Validation method	Temperature	Relative humidity	Wind Speed
Index of agreement	0.890	0.688	0.168
RMSE	2.455	16.624	0.819
MAE	1.889	12.814	0.593
Pearson correlation coefficient	0.934	0.768	-0.325

Figure 5 shows the predicted and measured values of relative humidity at monitoring point A. The divergence can be seen clearly for the time interval of 03:00-10:00, where the observed relative humidity value rises to its daily maximum due to the lower air temperature values at night. However, this impact is much smaller in the predicted values. For the rest of the day the predicted values seem to have a closer pattern behaviour to the observed ones with an average change value of 8.8%. Overall, the two sets of data present an adequate correlation, with an index of agreement value of 0.646 and Pearson correlation coefficient of 0.743 (Table 3).

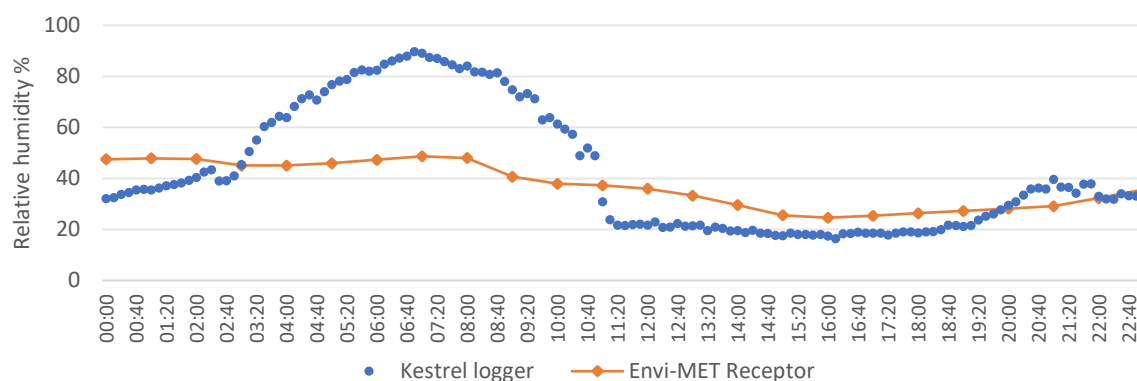


Figure 5. Data comparison between the observed and the predicted for relative humidity, location A.

As shown in Figure 6 for location B, RH values from Envi-MET at location B behave in a similar fashion to location A, with values having a large divergence between 03:00 and 10:00 with an average RH difference of 18.4%. compared to an average of 8.1% for the rest of the time. Overall, the data sets have an adequate correlation, with an index of agreement value of 0.688 and Pearson correlation coefficient of 0.768 (Table 4).

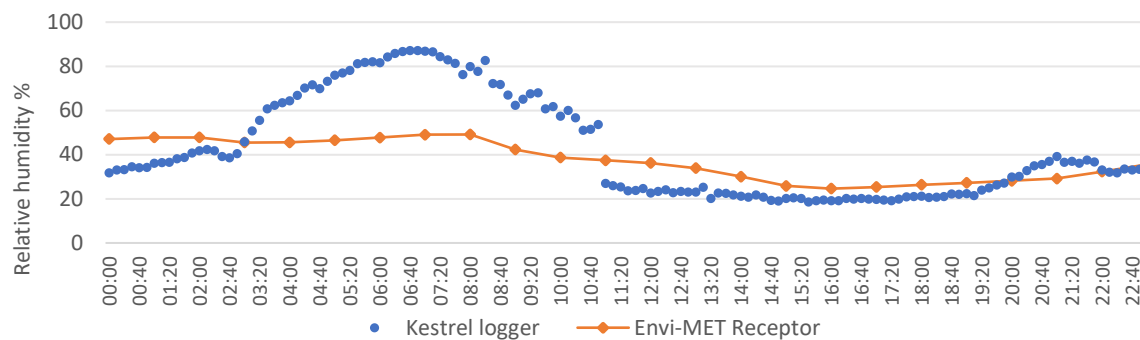


Figure 6. Data comparison between the observed and the predicted for relative humidity, location B.

Figures 7 and 8 indicate the predicted and observed values for wind speed; however, the predicted values for wind speed are averaged over an hourly basis, whereas the observed values were recorded every 10 minutes. The trend line shows great similarities with the predicted values, although there are large individual differences. In this case, even though the model validation methods in Tables 3 and 4 show a very low correlation, Envi-MET's results are still valid. This example shows the difficulty of trying to validate Envi-MET with a rapidly fluctuating parameter like the wind.

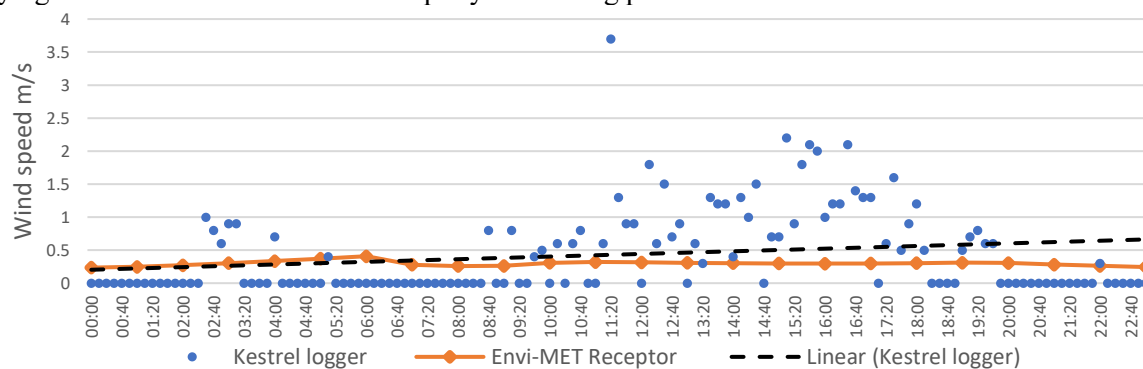


Figure 7. Data comparison between the observed and the predicted for wind speed, location A.

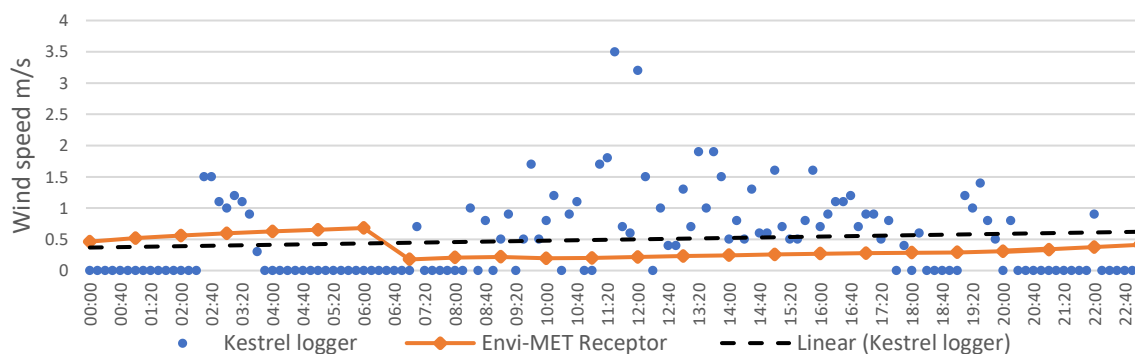


Figure 8. Data comparison between the observed and the predicted for wind speed, location B.

5.2. Envi-MET model sensitivity testing

For the purpose of testing Envi-MET's sensitivity, a series of model runs were made for different parameters. The tested area was comprised of 50 x 50 metre plots, with six 9-metre-high buildings surrounding the buildings. The model was run three times for every parameter, testing the base, the low and the high values of that said parameter. These parameters included relative humidity, wind speed, albedo and grid resolution. Air temperature was the derived parameter from running Envi-MET to test sensitivity to the range of inputs.

5.3 Wind Speed Sensitivity

Figure 9 shows the plotted data from the Envi-MET model testing the wind speed. A low wind of 1 m/s tended to lower the base model air temperature for 06:00-08:00 by an average value of 1.5°C, a maximum of 2.3°C and a minimum of 0.5°C. However, through the time interval of 09:00 to 17:00 the low wind speed showed a significant increase in air temperature, by an average of 1.8°C, a maximum value of 2.9°C and a minimum of 0.3°C. High wind speeds, on the other hand, showed a slight increase of air temperature for the same time intervals in the night time with an average of 0.4 °C, a maximum value of 0.8°C and a minimum of 0.1°C. Day time showed lower air temperature value, with an average of 1.1°C, a maximum value of 1.4°C and a minimum of 0.5°C.

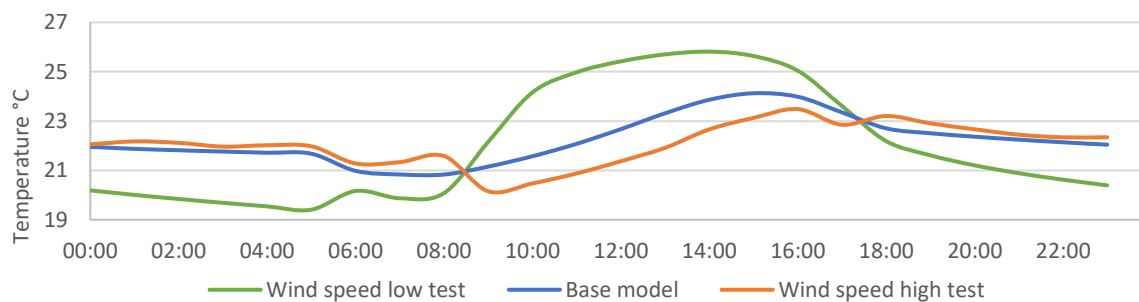


Figure 9. Wind speed sensitivity testing

5.4 Relative Humidity Sensitivity

Figure 10 shows the plotted data from the Envi-MET relative humidity testing. The low test value of 40% relative humidity showed a higher air temperature values compared to the base model for the time interval 11:0-17:00; the average change value was 0.3°C, while the maximum value was 1.0°C and the minimum value was 0.1°C. The low RH tended to lower the air temperature values for the time interval of 05:00-10:00, with an average change value of 1.0°C, a maximum value of 1.3°C and a minimum of 0.4°C. The air temperature values of the 90% relative humidity high test showed an average increase of 0.9°C for the time interval of 06:00 - 13:00 and a maximum value of 1.3°C and a minimum of 0°C. For the rest of the day, the high relative humidity tended to lower the base model's air temperature by an average value of 0.4°C, a maximum value of 0.8°C and a minimum of 0.3°C.

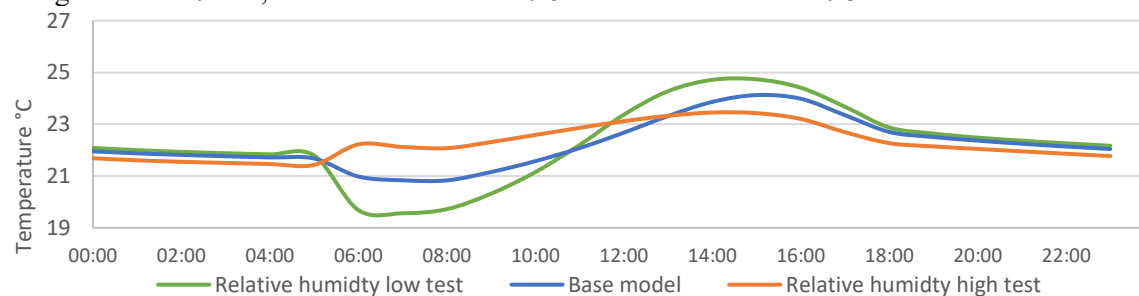


Figure 10. Relative humidity sensitivity testing

5.5 Albedo Sensitivity

Figure 11 shows the plotted data from the Envi-MET model testing the albedo. The albedo of the buildings' cladding and the pavement area were modified as low albedo of 10%, base model of 50% and high albedo of 90%. The high albedo test show virtually no change in the air temperature compared to the base model. However, the albedo test showed a slightly higher change in air temperature values

compared to the high albedo test, with an average change of 0.2°C and a maximum value of 0.3°C .

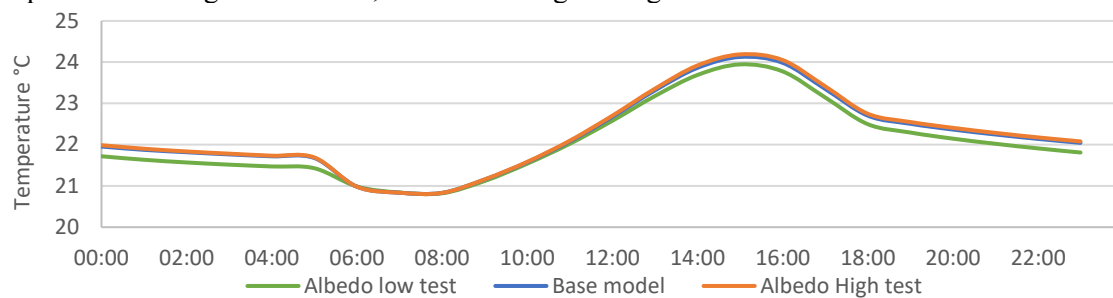


Figure 11. Albedo sensitivity testing.

5.6 Grid size

Simulating in Envi-MET relies heavily on the size of the actual project and in some cases the studied parameter. A higher resolution grid or a thicker mesh would give more accurate results that is if the site is relatively small. However, increasing the resolution of the grid will raise the hardware requirement and the simulation time. The base model that was used in the testing was a $50 \times 50\text{m}$ plot with a resolution of $1 \times 1\text{m}$. In order to test Envi-MET's sensitivity two other mesh counts were introduced: 2×2 and a 3×3 . As Figure 12 shows, the 3×3 grid's air temperature values had a large increase compared to the base model for the time interval of 13:00-03:00, with an average change value of 4.8°C , a maximum change value of 12.2°C and a minimum change value of 0.4°C . For the rest of the day the variations showed a decrease in air temperature values of an average change value of 2.8°C , a maximum change value of 4.2°C and a minimum change value of 0.1°C . The 2×2 grid had better accuracy than the other grids. However, air temperature values showed a decrease from the base model for the time interval of 14:00-09:00, with an average change value of 1.9°C , a maximum change value of 2.9°C and a minimum change value of 0.1°C . For the time interval 10:00-13:00 Figure 13 shows a slight increase in air temperature values of an average change value of 0.5°C , a maximum change value of 0.7°C and a minimum change value of 0.5°C .

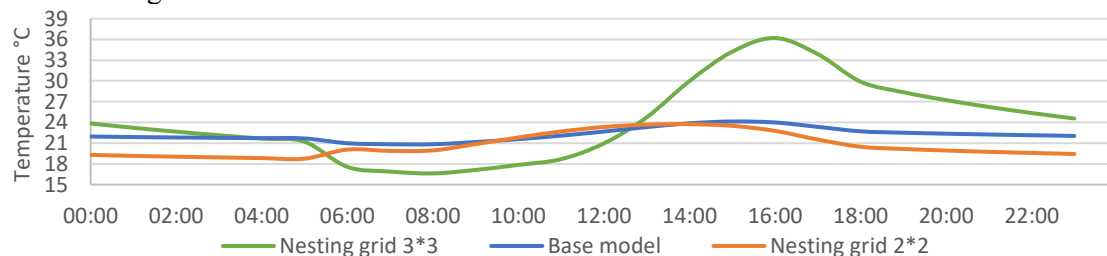


Figure 12. Grid size sensitivity testing.

6. Conclusion

Envi-MET showed different sensitivity levels across the tested parameters. The relative humidity change showed a good response to air temperature, especially at the highest value of the day, where the rise in relative humidity produced lower air temperature values and vice versa. For the wind speed Envi-MET also showed an effect in moving the air temperature compared to the base model. Air temperature had a significant increase when reducing the wind speed to a minimum but showed a smaller value change when increasing the wind speed to double the base model. Lowering the grid count was shown to produce inaccurate results compared to the base model, particularly when simulating small urban plots in Envi-MET using a small resolution, as seen for the 3×3 grid. However, the 2×2 grid showed less error percentage compared to the base model. The albedo test had the least impact on air temperature compared to the other parameters where it only showed a slight decrease in values in the low test.

Though Envi-MET has some unsatisfactory results, as with the relative humidity testing, it showed that the data reacted to air temperature change for night time to some extent, and it had a good correlation value for the rest of the day. The air temperature testing showed the most accurate results with the highest index of agreement values. As for the wind speed, Envi-MET showed a very good correlation

with the trend line of the observed values since it averaged the hourly data. Overall, the study showed that Envi-MET as a simulation software is better suited to analyse the relative change in parameters rather than the change in absolute values, as it shows a great response to the modification of microclimatic parameters.

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